

A Reproduced Copy

OF

JPL-Pub-87-13 VOL.R

(NASA-CR-184686) PROCEEDINGS OF THE
WORKSHOP ON SPACE TELEROBOTICS, VOLUME 2
(Jet Propulsion Lab.) 422 p CSCL 09B

N89-26492
--THRU--
N89-26540
Uncclas

G3/63 0188120

Reproduced for NASA

by the

NASA Scientific and Technical Information Facility

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

ABSTRACT

These proceedings report the results of a workshop on space telerobotics, which was held at the Jet Propulsion Laboratory, January 20-22, 1987. Sponsored by the NASA Office of Aeronautics and Space Technology (OAST), the workshop reflected NASA's interest in developing new telerobotics technology for automating the space systems planned for the 1990s and beyond. The workshop provided a window into NASA telerobotics research, allowing leading researchers in telerobotics to exchange ideas on manipulation, control, system architectures, artificial intelligence, and machine sensing. One of the objectives was to identify important unsolved problems of current interest. The workshop consisted of surveys, tutorials, and contributed papers of both theoretical and practical interest. Several sessions were held with the themes of sensing and perception, control execution, operator interface, planning and reasoning, and system architecture. Discussion periods were also held in each of these major topics.

ACKNOWLEDGMENT

Thanks are due to D.R. Meldrum, R.S. Doshi, K. Kreutz, H. Seraji, M.H. Milman, and S.K. Owen for significant contributions to the organization of the workshop.

CONTENTS

Volume I

PLINARY SESSION	1
Program Objectives and Technology Outreach P.S. Schenker	3
Building Intelligent Systems: Artificial Intelligence Research at NASA Ames Research Center P. Friedland and H. Lum	19
SYSTEM CONCEPTS	27
Space Telerobotic Systems: Applications and Concepts L. Jenkins	29
Laboratory Testing of Candidate Robotic Applications for Space R.B. Purves	35
Telerobotic Assembly of Space Station Truss Structure G. Fischer	45
Robotic Mobile Servicing Platform for Space Station S.H. Lowenthal and L. Van Erden	55
System Engineering Techniques for Establishing Balanced Design and Performance Guidelines for the Advanced Telerobotic Testbed W.F. Zimmerman and J.R. Matijevic	67
Dedicated Robotic Servicing for the Space Station R.F. Thompson, G. Arnold, and D. Gutow	75
Shuttle Bay Telerobotics Demonstration W. Chun and P. Cogeo	83
Telerobotics: Research Needs for Evolving Space Stations L. Stark	91
Robot Design for a Vacuum Environment S. Belinski, W. Trento, R. Imani-Shikhabadi, and S. Hackwood . . .	95
Multi-Limbed Locomotion Systems for Space Construction and Maintenance K.J. Waldron and C.A. Klein	105
Commercial Users Panel	113

SYSTEM ARCHITECTURE	125
Task Allocation Among Multiple Intelligent Robots L. Gasser and G. Bekey	127
Execution Environment for Intelligent Real-Time Control Systems J. Sztipanovits	131
Distributed Intelligence for Supervisory Control W.J. Wolfe and S.D. Raney	139
An Architecture for Heuristic Control of Real-Time Processes P. Raulefs and P.W. Thorndyke	149
Hierarchical Control of Intelligent Machines Applied to Space Station Telerobots J.S. Albus, R. Lumia, and H. McCain	155
Programming Methodology for a General Purpose Automation Controller M.C. Sturzenbecker, J.U. Korein, and R.H. Taylor	167
Real-Time Hierarchically Distributed Processing Network Interaction Simulation W.F. Zimmerman and C. Wu	173
Metalevel Programming in Robotics: Some Issues A. Kumar N. and N. Parameswaran	181
An Approach to Distributed Execution of ADA Programs R.A. Volz, P. Krishnan, and R. Theriault	187
Computational Structures for Robotic Computations C.S.G. Lee and P.R. Chang	199
A Run-Time Control Architecture for the JPL Telerobot J. Balaram, A. Lokshin, K. Kreutz, and J. Beahan	211
Distributed Control Architecture for Real-Time Telerobotic Operation H.L. Martin, P.E. Satterlee, Jr., and R.F. Spille	223
High Performance Architecture for Robot Control E. Byler and J. Peterson	233
Software and Hardware for Intelligent Robots G.N. Saridis and K.P. Valavanis	241
Nested Hierarchical Controller With Partial Autonomy A. Meystel	251

AUTONOMOUS SYSTEMS	271
3-D World Modeling With Updating Capability Based on Combinatorial Geometry M. Goldstein, F.G. Pin, G. de Saussure, and C.R. Weisbin	273
On Autonomous Terrain Model Acquisition by a Mobile Robot N.S.V. Rao, S.S. Iyengar, and C.R. Weisbin	283
SOLON: An Autonomous Vehicle Mission Planner M.J. Dudziak	289
Mission Planning for Autonomous Systems G. Pearson	303
Certainty Grids for Mobile Robots H.P. Moravec	307
Environmental Modeling and Recognition for an Autonomous Land Vehicle D.T. Lawton, T.S. Levitt, C.C. McConnell, and P.C. Nelson	313
GEOMETRIC REASONING	337
Telerobot Task Planning and Reasoning: Introduction to JPL Artificial Intelligence Research D.J. Atkinson	339
Geometric Reasoning R.F. Woodbury and I.J. Oppenheim	351
A Qualitative Approach for Recovering Relative Depths in Dynamic Scenes S.M. Haynes and R. Jain	361
A Framework for Qualitative Reasoning About Solid Objects E. Davis	369
Volume II	
SENSING AND PERCEPTION	1
The Sensing and Perception Subsystem of the NASA Research Telerobot B. Wilcox, D.B. Gennery, B. Bon, and T. Litwin	3
Knowledge-Based Vision for Space Station Object Motion Detection, Recognition, and Tracking P. Symosek, D. Panda, S. Yalamanchili, and W. Wehner III	952
Sensor Systems Testbed for Telerobotic Navigation A.W. Thiele, D.E. Gjellum, R.H. Rattner, and D. Manouchehri	1953

Monovision Techniques for Telerobots P.W. Goode and K. Cornils	23	<i>Sy</i>
Tracking 3-D Body Motion for Docking and Robot Control M. Donath, B. Sorensen, G.B. Yang, and R. Starr	31	<i>Sy</i>
Object Apprehension Using Vision and Touch R. Bajcsy and S.A. Stansfield	45	<i>Sy</i>
Sensory Substitution for Space Gloves and for Space Robots P. Bach-y-Rita, J.G. Webster, W.J. Tompkins, and T. Crabb	51	<i>Sy</i>
Electronic Prototyping J. Hopcroft	59	<i>Sy</i>
Multiple Degree of Freedom Optical Pattern Recognition D. Casasent	65	<i>Sy</i>
Maximum Likelihood Estimation of Parameterized 3-D Surfaces Using a Moving Camera Y. Hung, B. Cernuschi-Friis, and D.B. Cooper	71	<i>Sy</i>
The Architecture of a Video Image Processor for the Space Station S. Yalamanchili, D. Lee, K. Fritze, T. Carpenter, K. Hoyme, and N. Murray	85	<i>Sy</i>
An Optical Processor for Object Recognition and Tracking J. Sloan and S. Udomkesmalee	95	<i>Sy</i>
Improved Shape-Signature and Matching Methods for Model-Based Robotic Vision J.T. Schwartz and H.J. Wolfson	103	<i>Sy</i>
A Technique for 3-D Robot Vision for Space Applications V. Markandey, H. Tagare, and R.J.P. deFigueiredo	111	<i>Sy</i>
Differential Surface Models for Tactile Perception of Shape and On-Line Tracking of Features H. Hemami	125	<i>Sy</i>
Constraint-Based Stereo Matching D.T. Kuan	131	<i>Sy</i>
A Database/Knowledge Structure for a Robotics Vision System D.W. Dearholt and N.N. Gonzales	135	<i>Sy</i>
Sensing and Perception: Connectionist Approaches to "Subcognitive" Computing J. Skrzypek	145	<i>Sy</i>
Parallel Processing for Digital Picture Comparison H.D. Cheng and L.T. Kou	155	<i>Sy</i>

ROBOT SIMULATION AND CONTROL	163	004
Inverse Kinematic-Based Robot Control W.A. Wolovich and K.F. Flueckiger	165	520
Spatially Random Models, Estimation Theory, and Robot Arm Dynamics G. Rodriguez	177	521
Task Oriented Nonlinear Control Laws for Telerobotic Assembly Operations R.A. Walker, L.S. Ward, and C.F. Elia	185	522
A Universal Six-Joint Robot Controller D.G. Bihm and T.C. Hsia	197	523
Real-Time Graphic Simulation for Space Telerobotics Applications E.W. Baumann	207	524
Manipulator Control and Mechanization: A Telerobot Subsystem S. Hayati and B. Wilcox	219	525
Chaos Motion in Robot Manipulators A. Lokshin and M. Zak	229	526
Effect of Control Sampling Rates on Model-Based Manipulator Control Schemes P.K. Khosla	235	527
Kinematically Redundant Robot Manipulators J. Baillieul, R. Brockett, J. Hollerbach, D. Martin, R. Percy, and R. Thomas	245	528
Control Strategy for a Dual-Arm Maneuverable Space Robot P.K.C. Wang	257	529
A Space Systems Perspective of Graphics Simulation Integration R. Brown, C. Gott, G. Sabionski, and D. Bochsler	267	530
A Learning Controller for Nonrepetitive Robotic Operation W.T. Miller, III	273	531
TELEROBOTS	283	007
A Flexible Telerobotic System for Space Operations N.O. Sliwa and R.W. Will	285	532
Systems Simulations Supporting NASA Telerobotics F.W. Harrison, Jr. and J.E. Pennington	293	533
Coordination of Multiple Robot Arms L.K. Barker and D. Soloway	301	4

Development of a Semi-Autonomous Service Robot With Telerobotic Capabilities J.E. Jones and D.R. White	307 <i>S35</i>
A Task-Based Metric for Telerobotic Performance Assessment J.F. Barnes	317 <i>S36</i>
Motion Coordination and Programmable Teleoperation Between Two Industrial Robots J.Y.S. Luh and Y.F. Zheng	325 <i>S37</i>
Use of Control Umbilicals as a Deployment Mode for Free Flying Telerobotic Work Systems J.S. Kuehn and E.D. Selle	335 <i>S38</i>
The Design of a Nine-String Six-Degree-of-Freedom Force-Feedback Joystick for Telemomanipulation M.L. Agronin	341 <i>S39</i>
MAN MACHINE INTERFACE	349 <i>omit</i>
Issues in Human/Computer Control of Dexterous Remote Hands K. Salisbury	351 <i>S40</i>
Man-Machine Interface Issues in Space Telerobotics: A JPL Research and Development Program A.K. Bejczy	361 <i>S41</i>
Task-Level Testing of the JPL-OMV Smart End Effector B. Hannaford	371 <i>S42</i>
A Natural-Language Interface to a Mobile Robot S. Michalowski, C. Crangle, and L. Liang	381 <i>S43</i>
Types of Verbal Interaction With Instructable Robots C. Crangle, P. Suppes, and S. Michalowski	393 <i>S44</i>
MIT Research in Telerobotics T.B. Sheridan and Staff	403 <i>S45</i>
Telerobotics: A Simulation Facility for University Research L. Stark et al.	413 <i>S46</i>
Mixed-Initiative Control of Intelligent Systems G.C. Borchardt	423 <i>S47</i>
Report on the Stanford/Ames Direct-Link Space Suit Prehensor J.W. Jameson	433 <i>S48</i>

Volume III

PLANNING AND SCHEDULING: BASIC RESEARCH AND TOOLS	1
Planning and Scheduling: Is there a Difference? K.G. Kempf	3
The Mechanisms of Temporal Inference B.R. Fox and S.R. Green	9
Contingent Plan Structures for Spacecraft M. Drummond, K. Currie, and A. Tate	17
Reasoning and Planning in Dynamic Domains: An Experiment With a Mobile Robot M.P. Georgeff, A.L. Lansky, and M.J. Schoppers	27
Route Planning in a Four-Dimensional Environment M.G. Slack and D.P. Miller	41
Prediction and Causal Reasoning in Planning T. Dean and M. Boddy	49
The Generic Task Toolset: High Level Languages for the Construction of Planning and Problem Solving Systems B. Chandrasekaran, J. Josephson, and D. Herman	59
Monitoring Robot Actions for Error Detection and Recovery M. Gini and R. Smith	67
Recovering From Execution Errors in SIPE D.E. Wilkins	79
Incremental Planning to Control a Blackboard-Based Problem Solver E.H. Durfee and V.R. Lesser	91
Knowledge Representation System for Assembly Using Robots A. Jain and M. Donath	101
Real Artificial Intelligence for Real Problems R.S. Doshi	115
TRAJECTORY PLANNING FOR MANIPULATORS	117
The Use of 3-D Sensing Techniques for On-Line Collision-Free Path Planning V. Hayward, S. Aubry, and Z. Jasiukajc	119
Collision-Free Trajectory Planning Algorithm for Manipulators F. Pourboghrat and J.Y. Han	125

Task Planning and Control Synthesis for Robotic Manipulation in Space Applications	
A.C. Sanderson, M.A. Peshkin, and L.S. Homem-de-Mello	129
Using Automatic Robot Programming for Space Telerobotics	
E. Mazer, J. Jones, A. Lanusse, T. Lozano-Perez, P. O'Donnell, and P. Tournassoud	139
 MANIPULATOR CONTROL	151
 Manipulator Control: An Overview	
H. Seraji	153
 Adaptive Force-Position Control for Teleoperated Manipulators	
A.J. Koivo	155
 Adaptive Control of Dual-Arm Robots	
H. Seraji	159
 Design of a Reconfigurable Modular Manipulator System	
D. Schmitz and T. Kanade	171
 Nonlinear Feedback Control of Multiple Robot Arms	
T.J. Tarn, X. Yun, and A.K. Bejczy	179
 Dynamics and Control of Coordinated Multiple Manipulators	
S.A. Hayati	193
 A Survey of Adaptive Control Technology in Robotics	
S. Tosunoglu and D. Tesar	205
 Simple Robust Control Laws for Robot Manipulators, Part I: Non-adaptive Case	
J.T. Wen and D.S. Bayard	215
 Simple Robust Control Laws for Robot Manipulators, Part II: Adaptive Case	
D.S. Bayard and J.T. Wen	231
 Algorithms for Adaptive Control of Two-Arm Flexible Manipulators Under Uncertainty	
J.M. Skowronski	245
 Problems and Research Issues Associated With the Hybrid Control of Force and Displacement	
R.P. Paul	255
 Adaptive Hybrid Control of Manipulators	
H. Seraji	261
 Adaptive Hybrid Position/Force Control of Robotic Manipulators	
F. Pourboghrat	273

Flexible Manipulator Control Experiments and Analysis	
S. Yurkovich, Ü. Özgürer, A. Tzes, and P.T. Kotnik	279
Dual Arm Robotic System With Sensory Input	
Ü. Özgürer	289
Geometric Foundations of the Theory of Feedback Equivalence	
R. Hermann	299
Reducing Model Uncertainty Effects in Flexible Manipulators	
Through the Addition of Passive Damping	
T.E. Alberts	307
Parallel Processing Architecture for Computing Inverse Differential	
Kinematic Equations of the PUMA Arm	
T.C. Hsia, G.Z. Lu, and W.H. Han	317
Manipulator Control by Exact Linearization	
K. Kreutz	325
A Virtual Manipulator Model for Space Robotic Systems	
S. Dubowsky and Z. Vafa	335
Model Reduction for Discrete Bilinear Systems	
A.M. King and R.E. Skelton	345
High Gain Feedback and Telerobotic Tracking	
D.E. Koditschek	355
Concept Development of a Tendon Arm Manipulator	
and Anthropomorphic Robotic Hand	
C.T. Tolman	365
Future Research Directions	
Moderator: G.A. Bekey	
Panel Members: R. Bajcsy, J.Y.S. Luh, A. Sanderson,	G. Saridis, T.B. Sheridan, C. Weisbin,
	373
APPENDIX A	
Program Schedule	391
APPENDIX B	
Index by Author	405
APPENDIX C	
Attendees/Participants	409